The Formation and Evolution of Massive Young Star Clusters
ASP Conference Series, Vol. ., 2004
eds. H.J.G.L.M. Lamers, A. Nota & L. J. Smith

Life and Death of Young Dense Star Clusters near the Galactic Center

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Abstract. We discuss the structural change and degree of mass segregation of young dense star clusters within about 100 pc of the Galactic center. In our calculations, which are performed with GRAPE-6, the equations of motion of all stars and binaries are calculated accurately but the external potential of the Galaxy is solved (semi)analytically. The simulations are preformed to model the Arches star cluster. We find that star clusters with are less strongly perturbed by the tidal field and dynamical friction are much stronger affected by mass segregation; resulting in a significant pile-up of massive stars in the cluster center. At an age of about 3.5 Myr more than 90 per cent of the stars more massive than $\sim 10\,\mathrm{M}_\odot$ are concentrated within the half-mass radius of the surviving cluster. Star clusters which are strongly perturbed by the tidal field of the parent Galaxy are much less affected by mass segregation.

1. Introduction

In recent years a relatively new class of star clusters has been discovered. These systems are variously referred to in the literature as young populous clusters, super star clusters, proto-globular clusters, and even young globular clusters (although it remains unclear if they are in any way related to the old globular clusters observed in many galactic halos). We prefer the term "young dense cluster" (hereafter YDC, sometimes pronounced "YoDeC") because it highlights the key defining properties of these compact stellar systems. The fact that these clusters are young means that stars of all masses are still present, offering critical insights into the stellar initial mass function and cluster structural properties at formation. The term "dense" means that dynamical evolution and physical collisional processes can operate fast enough to compete with and even overwhelm stellar evolutionary timescales. Dense stellar systems are places where wholly

new stellar evolution channels can occur, allowing the formation of stellar species completely inaccessible by standard stellar and binary evolutionary pathways.

Table 1 presents an overview of known YDCs in the neighborhood of the Milky Way Galaxy, for which the relevant parameters are well determined. The clusters listed in the table are selected on the basis of age ($\lesssim 10$ Myr) and half-mass relaxation time ($\lesssim 100$ Myr); the latter criterion is not universally used, but it best reflects the interplay between dynamics and stellar evolution just described—clusters satisfying this condition are expected to experience significant dynamical evolution before their massive stars explode as supernovae. All the clusters in Table 1 thus lie in the regime where dynamical and stellar evolution cannot be considered independently.

In the paper we concentrate on the Arches star cluster, which was observed in detail by Figer et al (1999; 2002) and Stolte (2002). The ~ 3 Myr old Arches cluster is located at a projected distance of about 25 pc from the Galactic center, has a half mass radius of about 0.23 parsec and contains between 20 000 and 10^5 stars. Together with the Quintuplet star cluster (Glass 1987) they are the only young dense star clusters which are strongly perturbed by the tidal field of their parent Galaxy. McMillan et al (2004) discusses the internal dynamical evolution and the possibility of the formation of an intermediate mass black hole in the star cluster MGG-11 in the starburst galaxy M82 (see also Portegies Zwart et al 2004), where Baumgardt et al (2004) discusses the further consequences of the presence of such a black hole.

Figure 1 shows a composite image of various star clusters on the same scale. Among these are, next to some other YDCs the Arches and Quintuplet systems. For comparison we added images of the globular cluster M80, the Pleiades and the Trapezium cluster, the star forming region in Orion. We note that the latter three systems are not considered YDCs, but are added for comparison.

We make the distinction between two families of YDCs; those that are isolated and those that are strongly perturbed by the external tidal field of their parent Galaxy. We know only two clusters that are in the latter category, Arches

Table 1. Observed properties of selected young, dense star clusters, mainly in or near the Milky Way. Mass (M), age, tidal radius ($r_{\rm tide}$) and half-mass radius ($r_{\rm hm}$) are taken from the literature.

Name	ref	$\log M/{\rm M}_\odot$	log(age/yr)	location	$r_{\rm tide}$ (pc)	$r_{\rm hm}$ (pc)
Arches	a	4.8	6.5	GC	1	0.23
Quintuplet	b	4.2	6.6	GC	1	0.5
NGC 3603	c	4.3	6.5	disk	10	0.78
Westerlund 1	d	4.5	6.8	disk	10	0.2
R 136	e	4.7	6.5	LMC	> 20	0.5
MGG-11	f	5.5	7.0	M82	> 20	$1.2^\star$

References: a) Figer et al. (1999;2002;2004); b) Glass et al. (1987); c) Brandl (1999); d) Vrba et al. (2000); e) Brandl et al. (1996); f) McCrady et al. (2003)
* The projected half light radius $r_{\rm hl} = 1.2$ pc, and we take $r_{\rm hm} = \frac{4}{3} r_{\rm hl}$ (Spitzer 1987).

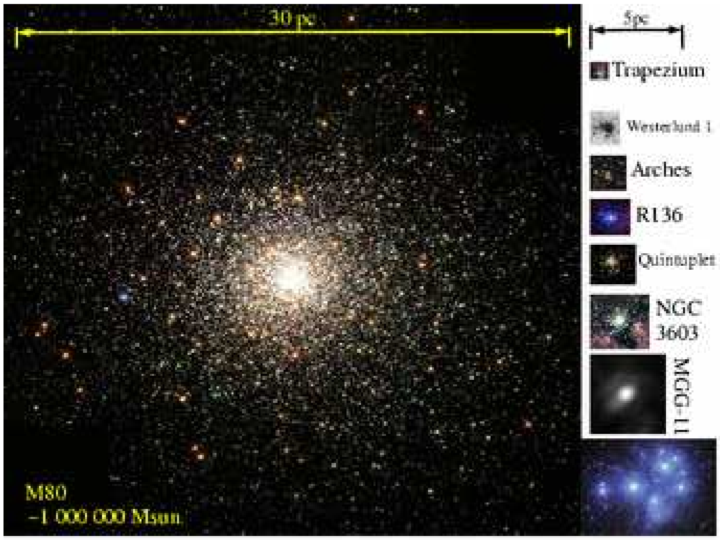

Figure 1. Composite image of several star clusters, all on the same scale. The big image to the left is the globular cluster M80. To the right are a selection of young dense star clusters, identified by their name (except the bottom image which represents the Pleiades star cluster.

and Quintuplet, the other YDCs are relatively unperturbed. The evolution of tidally perturbed or unperturbed clusters are profoundly different. In the limit of a strong tidal field, stars near the tidal radius of the cluster feel the proximity of the background Galaxy.

2. The simulation model and the initial conditions

We simulate young dense star clusters in the tidal field of the Galaxy. As initial conditions we use 65536 stars from a Kroupa (2003) initial mass function between the $0.1\,\mathrm{M}_\odot$ and $100\,\mathrm{M}_\odot$, 16 percent of which receives a (secondary) companion star with a mass between the adopted minimum stellar mass and the mass of the selected (primary) star. Orbital separations are selected from Roche-lobe contact to 5kT (about $300\,\mathrm{R}_\odot$), eccentricities are taken from the thermal distribution. The virial radius of all our models was 0.23 pc, and the density profile was selected to be a King model with $W_0 = 5$. These parameters are in agreement with the observed parameters for the Arches cluster (Figer et al. 2002; Stolte et al. 2002). We adopt these current parameters as initial conditions even though the cluster has experienced considerable dynamical evolution over the last ~ 3 Myr (Portegies Zwart et al 2002).

The star clusters are positioned in various orbits around the Galactic center and evolved until an age of 3.5 Myr. The age and orbital parameters are selected such that the cluster then is at a distance of about 30 pc from the Galactic center. We discuss the results of three simulations here; (1) a star cluster (model R30a) in a circular orbit at $R_{\mathrm{GC}} = 30$ pc from the Galactic

center, (2) a cluster which is born in apo-Galacticon at 30 pc from the Galactic center with 25 per cent of the velocity for a circular orbit (model R30b), and (2) a cluster with a velocity of 15 percent of the circular velocity at an apo-Galactic distance of 110 pc (model R110). In our calculations we solve the equations of motion of all the stars in the cluster, the orbit of the cluster and the evolution of the stars and binaries (see Portegies Zwart, McMillan & Gerhard, 2003, for details about the choice of the tidal field). We use the GRAPE-6 (Makino et al. 1997; 2003) to speed up the calculations and the simulations ware run with the `Starlab` software environment (Portegies Zwart et al. 2001) (see `http://www.manybody.org/starlab/starlab.html`).

3. Results

Each star cluster, once initialized, evolves internally while it orbits the Galactic center. Figure 2 (left frame) shows the inner 40 pc of the Galactic center with the orbits of three star clusters until an age of 3.5 Myr. In the right frame of figure 2 we present the mass of the two clusters in elliptic orbits as a function of time. The cluster in the circular orbit (R30a) in not plotted in this figure as it loses only ~ 3 per cent of its mass at a constant rate. The other two cluster on elliptical orbits, lose mass at a much higher rate. These clusters lose mass predominantly near pericenter, while hardly any mass is lost near apocenter. The average mass loss rates for these clusters is about 7200 $M_\odot$/Myr for model R30b and 4000 $M_\odot$/Myr for model R110, which are proportional to the relaxation time of these clusters at the tidal radius at the moment of pericenter, consistent with the expression derived by Portegies Zwart & McMillan (2002).

The large (downward) spikes in the bound mass is mainly a result of the fluctuating energy budget of the cluster due to binary evolution and dynamical interactions involving binaries. Interesting to note is that the binary fraction of the surviving clusters is about a factor two higher than initially.

Figure 3 depicts the stellar positions of the three clusters at an age of about 3.5 Myr for models R30a (top left), R30b (bottom left) and model R110 (right). At a distance of 30 pc from the Galactic center dynamical friction is rather inefficient and cluster R30a hardly sinks to the Galactic center on this short time scale (see also McMillan & Portegies Zwart 2003). The structure of the tidal debris in model R30a is a result of the low velocity of the escaped stars, which follow epicyclic motions around the co-moving fourth and fifth Lagrangian points of the combined potential of the cluster and the background Galaxy. These density enhancements persist with time, but may be hard to observe as they contain mainly low mass stars. However, we encourage observers to investigate the surroundings of the Arches and Quintuplet clusters to find evidence for these 'Trojan' stars or other signatures of tidal debris.

The lower-left panel in Fig. 3 shows the cluster R30b, which was on an elliptic orbit. The obits of the stars which escape from the cluster are slightly different than the orbit of the cluster, which continues to be shocked again on each subsequent passage, releasing even more stars. The mass loss rate per pericenter passage, however, is rather constant. Due to its rather rapid evaporation this cluster is hardly affected by mass segregation (see Fig. 4).

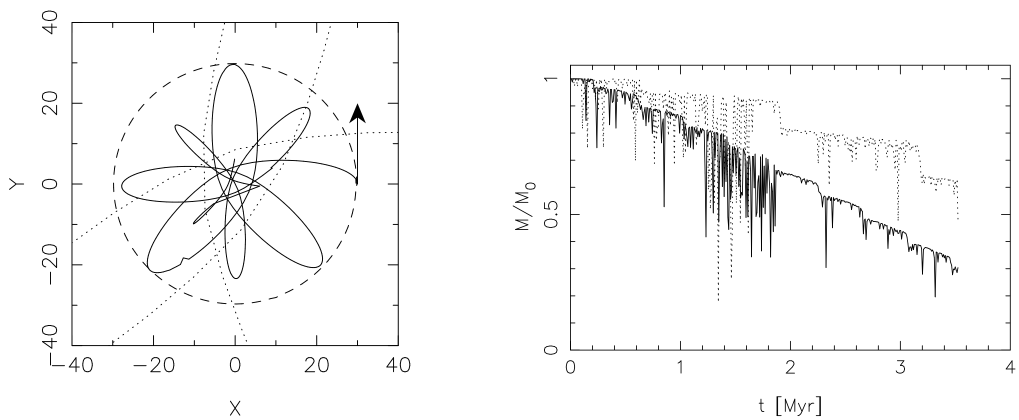

Figure 2. **left:** Orbit of three simulated star clusters ($W_0 = 5$, $N = 65536$, $r_{\rm vir} = 0.23\,$pc) one in a circular orbit around the Galactic center (R30a: dashes), the other with a initial orbital velocity of one quarter the circular velocity (R30b: solid curve), the third cluster was born at a distance of 110 pc from the Galactic center with velocity 15% of the circular velocity (R110: dotted line). The trajectories are plotted until an age of 3.5 Myr. The arrow indicate the direction of the initial velocity of the clusters born at $R_{\rm GC} = 30\,$pc.
Right: Evolution of the cluster mass for the models R30b (solid) and R110 (dotted line) both are on elliptical orbits.

The right panel in Fig. 3 shows the cluster model R110 which was born at a distance of 110 pc from the Galactic center with 15 per cent of the circular velocity, making the cluster orbit quite radial. The evolution of such cluster is relatively unperturbed by the tidal field until first pericenter passage, which happens for the first time around 0.6 Myr. The distribution of the stars at an age of 3.5 Myr is presented in Fig. 3. Pericenter passage was reached some time earlier, at around 3.2 Myr, and the cluster now approaches apocenter again.

Figure 4 shows $f(m > X)$ the present day mass function within the half-mass radius of the surviving cluster as fraction of the initial mass function. The distributions are cumulative toward higher mass. For $m \sim 0.1\,{\rm M}_\odot$ this results in about $f(m > X) \simeq 0.5$ confirming that we indeed compare the present day mass function at about the half mass radius with the initial mass function. This curve starts to deviate from $f(M > X) \simeq 0.5$ for higher mass stars, indicating that these stars are overrepresented within the half mass radius. The star cluster in a circular orbit at $R_{\rm GC} = 30\,$pc (mode R30a) is most strongly affected by mass segregation. For example, well over 90 per cent of the stars with $m \gtrsim 25\,{\rm M}_\odot$ ($\log(m/{\rm M}_\odot) \gtrsim 1.4$) are present within the half-mass radius of the surviving cluster.

The star cluster born at $R_{\rm GC} = 30\,$pc but with an elliptic orbit (solid curve, model R30b) is least effected by mass segregation. This is mainly caused by the rapid stripping of the cluster outer parts due to the strong tidal field (see Fig. 2). The cluster which was born at large distance form the Galactic center $R_{\rm GC} = 110\,$pc (model R110) is still strongly affected by mass segregation even

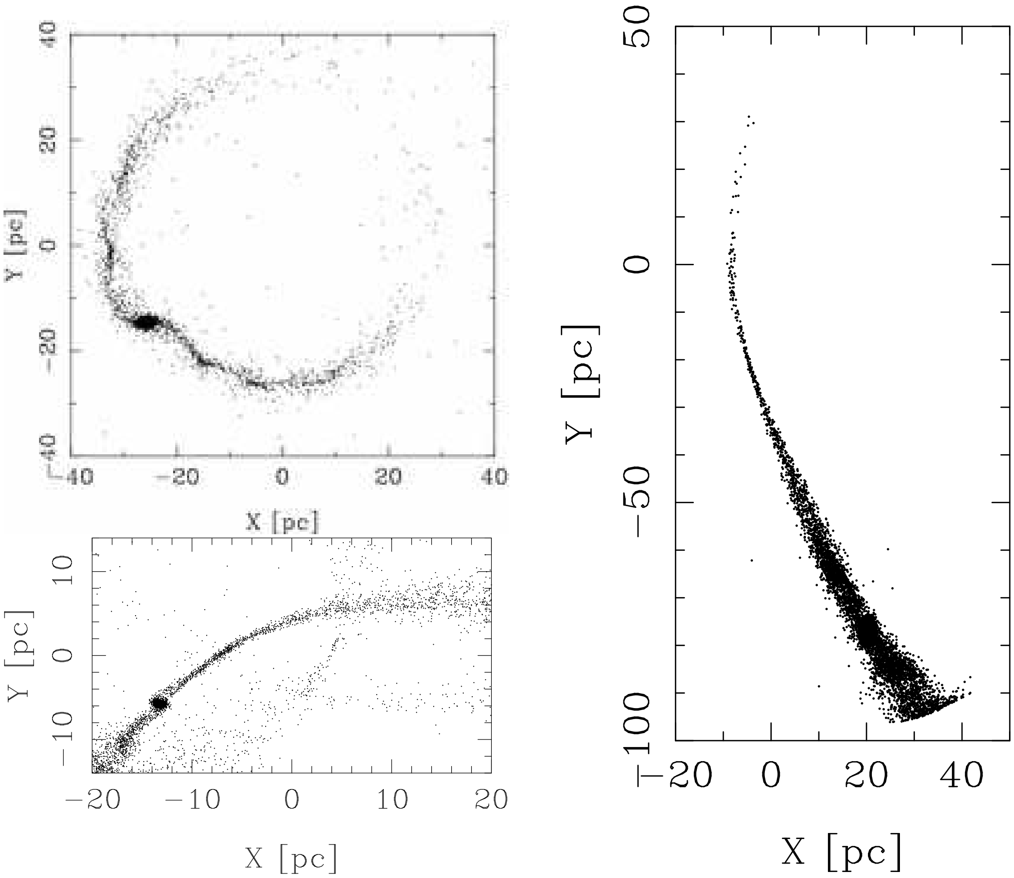

Figure 3. Stellar positions at an age of about 3.5 Myr for three simulated star clusters ($W_0 = 5$, $N = 65536$, $r_{\rm vir} = 0.23$ pc).
Left-Top: Calculation (R30a) with an initial circular orbit starting a $R_{\rm GC} = 30$ pc. This cluster has orbited the Galactic center more than three times in 3.5 Myr. Most ($\sim$ 97 per cent) stars are still cluster members, and the escaped stars remain on more or less the same orbit as the cluster.
Left-Bottom: Calculation (R30b) in an initial orbit with 25% of the circular velocity and $R_{\rm GC} = 30$ pc. The small velocity has as a consequence that the cluster passed the Galactic center at small distance, resulting in strong tidal perturbations to the cluster. The stars which became unbound at peri-Galacticon persist in their orbit, whereas the orbit of the cluster is deflected by dynamical friction.
Right: Calculation (R110) with $R_{\rm GC} = 110$ pc and with a velocity 0.15 of the circular velocity. Last peri-Galacticon passage occurred at an age of about 3.2 Myr.

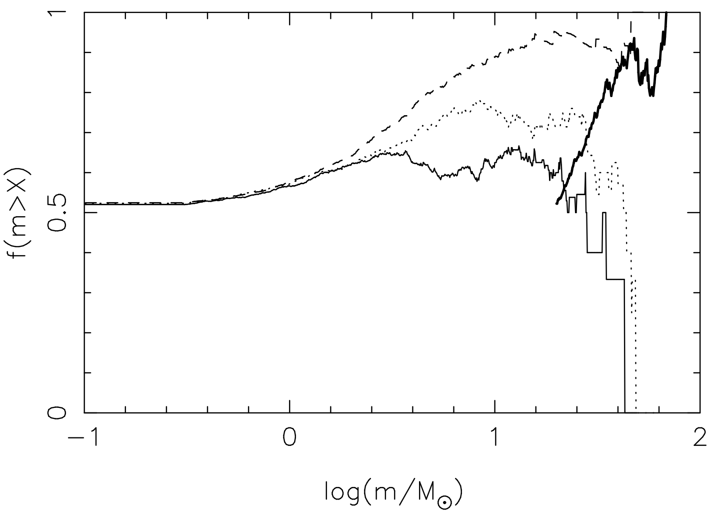

Figure 4. Cumulative present day mass function within the surviving cluster's half mass radius as fraction of the initial mass function. The dashed curve is for the simulation in a circular orbit, the lower solid curve is for the simulation at $R_{\rm GC} = 30\,{\rm pc}$ in an elliptic orbit and the dotted line represents the star cluster with initial $R_{\rm GC} = 110\,{\rm pc}$ in an elliptic orbit. Thick solid line (upper right) is taken from the Arches observations by Figer (2002) normalized to a Scalo (1986) initial mass function.

though the orbit brings it quite close to the Galactic center. Around the time of pericenter passage the outer parts of the cluster are stripped, but it takes about 0.6 Myr to pass the Galactic center for the first time. This time is sufficient to allow a considerable fraction of the high mass stars to segregate to the cluster center which, at an age of 3.5 Myr, is rich in high mass stars.

The thick solid curve in figure 4 represents the observed excess of massive stars ($m > 20\,{\rm M}_\odot$) from the observations of the Arches cluster by Figer et al. (2002), which was normalized to the Scale (1986) mass function at the minimum mass of $\sim 20\,{\rm M}_\odot$ for which Figer (2002) claims to be complete. The increasing incompleteness toward lower mass stars in these observations makes the normalization to this extend hard, but we can nicely compare the high-mass end which, for stars $\gtrsim 40\,{\rm M}_\odot$ is rather consistent with cluster model R30a, and inconsistent with the other simulations. From this comparison we conclude that the large over-abundance of high-mass stars in the Aches cluster is consistent with a mass function that is strongly affected by mass-segregation, like in model R30a, but inconsistent with the weakly segregated mass function of the strongly perturbed cluster R30e.

4. Conclusions

We perform simulations of young dense star clusters of 65536 stars of which 10486 have a close binary companion. The clusters are initially on three different

orbits around the Galactic center. At an age of 3.5 Myr we compare the mass function of the surviving cluster with the observed present day mass function of the Arches cluster. From this comparison we conclude that the present-day mass function of the Arches cluster is highly dynamically evolved. In the case this effect is due to the dynamical evolution of the cluster, we conclude that the cluster is not on an elliptic orbit which brings it within about 15 pc from the Galactic center.

Acknowledgments

We are grateful to Jun Makino and Piet Hut for numerous discussions, and in particular to Jun for the excessive use of his GRAPE-6, on which these simulations are performed. Additional simulations are performed at the GRAPE-6 systems at Drexel University and at the University of Amsterdam. This work was supported by NASA ATP, the Royal Netherlands Academy of Sciences (KNAW), the Dutch organization of Science (NWO), and by the Netherlands Research School for Astronomy (NOVA).

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